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Fine-scale quantification of streambank geomorphic volume loss caused by cattle access

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Abstract

Unrestricted cattle access to streams and rivers can be a significant source of pollution in fluvial systems, contributing to bank erosion and fine sediment inputs. Despite this pressure, observational data are scarce. This study quantified stream bank geomorphic modifications caused by cattle access at fine scale using motion-capture cameras and Terrestrial Laser Scanning (TLS) campaigns. Continuous monitoring of rainfall, discharge, conductivity and turbidity further augmented this dataset. The application of these techniques extended over a five-month grazing period in agricultural sub-catchments with intensive cattle production. At low flow, high-resolution water quality data showed that the frequency of cattle activity in and around stream margins was associated with elevated turbidity signals downstream. However, when elevated turbidity coincided with high flow events, it was not possible to distinguish between local erosion and upstream sediment transfers. TLS results indicated a loss of 0.141 m^3 to 1.035 m^3 stream bank material, which equates to 0.067 m^3 m^{-2} to 0.092 m^3 m^{-2} of stream bank area (between 27 % and 41 % in the <2 mm fraction) over the study period from sites with 130 to 1,154 discrete cattle access hits. Multiple linear regression showed that the observed geomorphic volume loss could not be explained by natural processes alone (hydrometeorology), but was more significantly related to cattle-access frequency as the principal driver. The geomorphic volume loss had the potential to impact 29 m^2 to 197 m^2 of stream bed with fine sediment (<2 mm) from the three study sites. Grazing parcels adjacent to streams in the study sub-catchments were enumerated at 18.4 parcels km^{-2} and so the results of this investigation potentially scale to a considerable fine sediment risk. Regulations and time-limited incentives to exclude cattle access to stream channels should therefore expect to reduce sediment pressures where these measures are targeted at access points.

Keywords: water quality, sediment, cattle access, erosion, terrestrial laser scanning, motion-capture cameras

1. Introduction

Among diverse point sources of nutrients or sediment, cattle access to rivers and streams is considered a worldwide issue in grassland systems with field-based livestock (see Miller et al., 2010 – Canada; Conroy et al., 2016 – Ireland; Hughes et al., 2016a – New Zealand; Terry et al., 2014 – UK; Schwarte et al., 2011 – United States). Key livestock pressures on the aquatic ecosystem include manure and urine deposition instream, trampling and erosion of fields and stream banks and disturbance of the river bed.

Cattle can be a significant cause of sediment inputs to river systems owing to their size and powerful locomotive effort which drives erosional and incisional mechanisms resulting in geomorphic alterations. This excessive soil damage, or 'poaching' effect (Collins et al., 2010; O'Callaghan et al., 2019; Sear et al., 1995), disturbs the soil surface, providing a source of material which can be mobilised either by rainfall or livestock movement and can lead to high sediment inputs to surface drains, streams and rivers (Belsky et al., 1999). Soil compaction (Sharrow, 2007), increased sedimentation (Hansen et al., 2010) and a reduction in soil infiltration rates (Castellano and Valone, 2007) can follow and lead to stream bank instability (Zaimes and Schultz, 2011). This instability is of particular concern during high streamflow, when cattle access has caused localised damage to banks leading to selective patches of bare land more vulnerable to further erosion. This can facilitate substantial volumes of sediment being released into the stream network (Evans et al., 2006; Magner et al., 2008).

Seasonally low soil cover and direct stream bank erosion have been cited as major sources of sediment loss from land to water in agricultural catchments (Sherriff et al., 2015). The latter provides a source in grassland catchments where direct soil surface erosion can be limited (Sherriff et al., 2018). Livestock access points are likely to be more discrete erosion sources, but the majority of previous research has focused on determining the effects in semi-arid regions. This includes Australasia and Canada, particularly dairy farms (Amy and Robertson, 2001; Miller et al., 2018) and the United States, focusing mainly on rangelands (Neal and Anders, 2015; Zaimes and Schultz, 2015). In NW Europe, particularly in regions such as Ireland and areas of the UK where grassland-based livestock farming dominates, studies have focused on the biological and chemical impacts of livestock access on water quality (e.g. Conroy et al., 2016; O'Sullivan et al., 2019a, b; Wilson and Everard, 2018). Indeed, Ireland will exclude cattle from water courses through fencing in early 2021 as a statutory policy for the most intensive livestock farms (SI 605, 2017). Other time-limited incentives for riparian fencing have been included in environmental management schemes in Scotland (Scottish Government, 2019) and Wales (Welsh Government, 2017). Despite this, there has been limited research on the geomorphic stream bank impact of cattle access and consequently, little is known on the extent to which cattle access points add to sediment inputs or how they influence bank erosion and destabilisation. Furthermore, there is a knowledge gap on whether these landforms are significant sources of sediment transfers relative to other forms of disturbance such as flooding.

There are numerous methodologies employed to measure river bank stability (e.g. long-term in channel morphology changes - Ziliani and Surian, 2012; turbidity fluctuation monitoring - Mitchell et al., 2003; in-situ shear stress tests - Micheli et al., 2002; erosion pins - Henshaw et al., 2013). However, applications have been limited by difficulty in utilisation, resolution of measurements and the timeframe of interest, and by operator bias (Nasermoaddeli and Pasche, 2008; Resop and Hession, 2010). One emerging tool that can be employed to mitigate these limitations is terrestrial laser scanning (TLS). TLS has demonstrated the capability to generate high-resolution digital terrain models (DTMs) by producing a detailed 3-D point cloud describing the topographic surface being investigated to sub-centimetre grid resolution in a variety of environmental systems (Day et al., 2013; Longoni et al., 2016). For example, it has been previously applied to observe a wide variety of geomorphological phenomena in aeolian (e.g. Cornwall et al., 2018), glacial (e.g. Prantl et al., 2017) and fluvial (Brasington et al., 2012) environments. Despite some studies employing TLS to investigate river bank structure and change over time (Teruggi et al., 2011; Prosdocimi et al., 2015) none have quantified bank erosion rates caused by cattle assess to stream channels. Therefore, in an economic climate of agricultural intensification (Melland et al., 2018) this study aimed to increase knowledge of cattle impacts on rivers and determine how this interaction affects bank erosion and destabilisation.

The objectives were to:

i. Determine whether the frequency of cattle access to rivers from adjacent grazing land at vulnerable sites had links to conductivity/turbidity impacts.
ii. Determine the importance of cattle access and hydrometeorological pressures on stream bank geomorphic volume loss.

2. Methodology

2.1 Site selection and characterisation

The study area was located in grassland sub-catchments of the intensively farmed Upper Bann river catchment in Northern Ireland (Figure 1). The wider catchment, which is 220 km^2 in area to the downstream monitoring point at Banbridge (50m Ordnance Datum), rises in the Mourne Mountains in the south (630 m Ordnance Dautm) and flows north toward Lough Neagh (surface area 392 km^2). Key physiographic features are sandstone and shale greywacke metasedimentary (Silurian) geology, overlain by glacial till in the form of drumlins and ribbed moraines. Soils are mostly gleyed with areas of brown earth, peat and alluvial deposits of silt, sand, and gravel. The landscape has a high drainage density (mean 1.44 km km^{-2}); annual mean precipitation over the period 1975 – 2016 was 600–800 mm in the lowlands and increasing to 800–1200 mm in the uplands (National River Flow Archive, 2016).

Three stream bank study sites (Figure 1) were selected in two sub-catchments (Bx and By) with second order streams, one under intensive management (Bx) and the other less intensive (By). Soils located at Site 1 (Bx) comprise of groundwater gley on alluvium with Sites 2 and 3 (By) consisting of brown earth on sandstone till (1:50,000 General Soil Map of Northern Ireland, AFBI, 2009). Other physiographic and land use/land cover details for the study sub-catchments and wider catchment are summarised in Table 1.

Figure 1.

Table 1.

Study sites in the sub-catchments were routinely grazed by livestock and were selected for investigation based on management practice, including grazing patterns of beef and dairy cattle. The three sites centred on cattle access points to the stream channel, at trampled zones which showed signs of regular disturbance, each between 2.0 and 7.5 m in length. The timeframe for this investigation was set between 18th July and 11th December 2018 due to grazing taking place from mid-summer (July) to early winter (December) with one stream bank at each site remaining unfenced for the duration of the investigation (lasting between 120 to 150 days depending upon sampling location). Livestock unit (LU) herd sizes with access to the stream points were twenty-eight beef cattle at Site 1 and eighty-five dairy cattle at Sites 2 and 3. As is normal in these agricultural settings, access points were left undisturbed prior to the start of grazing and exposed only to normal rainfall and river discharge events.

Stream gradients at each location were similar in profile with channel widths ranging from 2.05 – 4.15 m with low, steep-sided and vertical banks (Table 2). Discharge rate was measured at 5-minute intervals at the catchment outlets using a rated flat-v weir in conjunction with an OTT Orpheus Mini pressure transducer located > 1 m upstream of the weir installed within a stilling well. Daily rainfall data were obtained from an automatic UK meteorological rain gauge located at Katesbridge, Co. Down (+54°.297 N, -6°.110 W), approximately 2.67 km from the nearest sampling point and 8.5 km from the farthest point (Figure 1).

Table 2.

2.2 Monitoring cattle instream activity

The frequency and impact of cattle access to the stream channel were captured using a Victure HC200 motion-activated camera with infrared night vision, positioned at an elevated vantage point at each location. Each camera recorded images at a resolution of 1080 psi and offered a 120 ° detection angle with a trigger distance of up to 30 m, thus providing adequate coverage of the study areas.

Images were routinely downloaded and inspected for numbers of cattle entering the stream. A definite 'hit' was determined when one or more body parts was visible in the stream (illustrated by three animals recorded instream, Figure S1). Time-stamped hits were then grouped for analysis based on the frequency of access between subsequent TLS surveys. Therefore, the model parameter 'cattle access'was measured as the sum of recorded times cattle gained access to the channel over the specified time interval (i.e. between TLS surveys).

2.3 Monitoring of water quality parameters

Automated multi-parameter water quality sondes were deployed downstream from the cattle access points at Sites 1 and 3 throughout the investigation (Figure 1). Turbidity and conductivity data were recorded at 15-minute intervals using a YSI 6920 V2-2 sonde placed 15 m from the cattle access point at Site 1. Similarly, turbidity and conductivity (reference temperature 25 °C) were also recorded at Site 3 at the same data collection interval using an AquaTROLL 600 located 25 m from the access point (Figure 1). Water quality measurements were then synchronised and plotted against instream cattle access observations to determine if there was any association between instream access and water quality.

2.4 Terrestrial laser scanner: data acquisition and processing

To quantify the volumetric change of bank erosion taking place before, during and after cattle access to the stream channel TLS surveys were carried out between 18th July and 11th December 2018. At each sample point between four and six successive topographic surveys were conducted throughout the campaign depending upon sampling location.

The TLS data were captured using a FARO Focus^{3D} X330 single return terrestrial laser scanner operating at a laser beam wavelength of 1550 nm (FARO, Lake Mary, FL, USA). Between four and six reference spheres were deployed as ground control points for each scan, enabling multiple scans to be stitched together for each survey. This procedure of attaching retroreflective spheres to the same stationary position as in previous surveys, allowed all surveys to be referenced to these common reference points in order to identify change.

The annually calibrated FARO instrument has a scan distance range between 0.6 mm and 330 m encompassing a manufacturer specified ranging error of ± 2 mm at 10 m and a ranging noise error of 0.3 mm with 90% reflectance and 0.4 mm with 10 % reflectance. However, with greater distances, error and noise estimates increase. Therefore, for this investigation, all measurements were collected approximately 0.5 - 2 m from the cattle access point, well within the 10 m distance error estimates outlined and capturing an average 28 million data points per scan depending upon the distance away from the instrument.

Processing of the terrestrial laser scanning data included: a) preprocessing and data filtering, b) scan registration c) point cloud creation d) data cleaning and e) 3D mesh creation. Steps a-c were carried out using Faro SCENE® software (FARO Technologies UK LTD, Warwickshire, UK) and steps d and e were completed using 3DReshaper® software. Additionally, to identify areas of surface change CloudCompare v2.10; (http://www.cloudcompare.org) software was used in conjunction with the Multiscale Model to Model Cloud Comparison (M3C2) plugin algorithm. The M3C2 method is used to detect topographic change through analysing and computing differences between the repeated TLS point cloud scans at each site. Once preprocessing was completed, individual scans were then co-registered with the stationary retroreflective spheres. This consolidation or alignment is undertaken to assure all scans are in a single and universal coordinate system.

Following vegetation correction by digital removal of remnant data obscuring bare earth data (Day et al., 2013; Resop et al., 2012), meshing of the 3D point clouds was used to generate a surface model of the scene in 3DReshaper® resulting in a full 3D high-resolution mesh of the cattle access points and subsequent erosional points. Final overall geomorphic volume change observed at each study site was determined by calculating the difference in surface volume change between the first and last TLS based on ensuring low mean target distance errors (mean < 5.32 mm – Table S1). A workflow of these steps is shown in Figure S2.

2.5 Stream bank characteristics

Following Das et al. (2018), material was collected from the stream bank face at a depth of approximately 30 cm across the bank profile at each site. Ten samples were collected from each study location, composited and air-dried at room temperature, disaggregated using a pestle and mortar, and sieved (2 mm). Using a subsample of material for each location, particle size distribution was determined to quantify the <2 mm fraction as well as percentages of clay (<4 μm), silt (>4 to <62.5 μm) and sand (>62.5 to <2000 μm) (Ministry of Agriculture Fisheries and Food, 1986).

2.6 Statistical analysis

The pressures on stream bank erosion and hence geomorphic changes were assumed to be due to the magnitude of cattle access but with added pressures relating to hydrometeorology. Therefore, multiple linear regression analysis was undertaken to determine the relationship between geomorphic volume change as the dependent variable and cattle access frequency, rainfall and stream discharge as the predictors. All statistical analysis was undertaken with R 3.6.0 in the 'glm' library and 'stats' package (R Core Team, 2019). Variations of model predictors were tested and levels of significance used to infer model strength.

3. Results

3.1 Instream cattle access observations

A combination of field observations and analysis of digital images indicated that cattle were present at the study sites for 122, 14 and 5 days for Sites 1, 2 and 3 respectively. Throughout the investigation, a total of 1905 images were downloaded from the cameras and enumerated for cattle activity in and around the streams. Across all three study sites 1579 of the examined images were classified as hits with evident instream access. The remaining 326 images were determined to be either false triggers (e.g. vegetation, wildlife or rainfall) or images without confirmed cattle instream access and were therefore omitted. Site 1 had the highest frequency of instream activity with a total of 1154 confirmed observations with Sites 2 and 3 having 295 and 130 hits, (Table 3), i.e. each animal accessed the stream an average of 41.2, 3.5 and 1.5 times throughout the study period, respectively.

Table 3

3.2 Associations between instream cattle activity and water quality

The photographic data revealed that, once a lead animal entered the stream channel, others tended to follow in rapid succession, resulting in clusters of instream access leading to focused trampling activity. While instream, the majority of cattle remained stationary for extended periods usually during periods of drinking or grazing riparian vegetation. For typical channel access by small groups of two to six animals, cattle spent between 30 seconds and 6 minutes trampling the stream bed and banks. These movements affected the amount of sediment entering the water as a result of direct access to the stream bank or via resuspension from the bed.

Periods of access to the stream bank and bed were captured by turbidity and conductivity time series data during periods of low stream discharge. Despite some gaps in data collection due to power failures, data collected downstream from access points at Site 1 showed that water quality parameters were closely associated with instream cattle counts. For example, this association was particularly strong from 24th September 2018 to 12th October 2018 at Site 1 with a period of relatively high turbidity (up to 133 NTU from a base line average of 9 NTU) and conductivity (up to 626 µS cm^{-1} from a base line average of 392 µS cm^{-1}) during and after extensive instream access beginning at 9th October 2018 (Figure 2a). While elevated readings of water monitoring parameters occurred during periods of cattle access, turbidity responded with even higher increases during periods of storm discharge where conductivity decreased through dilution. These processes are shown in Figure 2b at Site 1 during the period from 23rd October 2018 to 20th November 2018 where a period of excessive cattle access during low stream flows showed increased turbidity (to > 100 NTU) and conductivity (up to approximately 800-1,200 µS cm^{-1}). Storms during mid-November, however, increased turbidity to >1,500 NTU, diluted conductivity to approximately 400 µS cm^{-1} and indicated increased turbulence and hydrological energy as the strongest agents of turbidity (and hence sediment) change. These periods do not, however, discriminate between the turbidity impacts of storm erosivity originating from the immediate cattle access points or those originating from wider sub-catchment diffuse sources.

Figure 2

3.3 Soil texture, bank erodibility and TLS

Soil analysis determined that stream banks across all three study sites comprised predominantly of material with a particle size > 2 mm in diameter with 62 %, 73 % and 59 % at Sites 1, 2 and 3 (i.e. 38 %, 27 % and 41 % fine sediment <2mm, respectively). For the latter fraction full particle size analysis subsequently indicated soil textural classes of clay loam, sandy silt loam and sandy loam (Table S2).

Surface change which occurred before and after instream cattle access (e.g. between first and last TLS surveys) is shown in Figure 3 and highlights areas of significant detectable change (See Figure S3-S5 for TLS detected change in each interval between TLS surveys). Modelling of surface retreat indicated concentrated erosion along the top and vertical face of the bank at Site 1 as depicted by erosional hotspots illustrated in red. Sites 2 and 3 indicated more stability with regard to surface vertical change as depicted by the M3C2 algorithm (Figure 3b and c). Geomorphic change calculated from the difference between first and last TLS survey showed that Site 1 had a total cut volume (eroded material) of 1.035 m^3 with Sites 2 and 3 having cut volumes of 0.537 m^3 and 0.141 m^3, respectively (Table 4). These volumes equate to 0.092 m^3 m^{-2}, 0.067 m^3 m^{-2} and 0.071 m^3 m^{-2} normalised by the area of impacted stream bank, respectively. Using cattle access frequency data (Table 3) and LU sizes at each site, the total cut volume losses also equate to 0.025 m^3 LU^{-1}, 0.153 m^3 LU^{-1} 0.094 m^3 LU^{-1}, respectively, over the grazing period. Small volumes of accretion (fill) occurred on all three sites, but this was material that had already been eroded upslope and was then deposited downslope. Also shown in Table 4 are rainfall and stream discharge between TLS surveys.

Based on these total cut volumes and the estimated percentage of material <2 mm diameter, the losses equate to 0.393 m^3, 0.145 m^3 and 0.058 m^3 fine sediment (0.035 m^3 m^{-2}, 0.018 m^3 m^{-2} and 0.029 m^3 m^{-2} of eroded stream bank area), respectively.

Figure 3

Table 4

3.4 Factors influencing stream bank geomorphic change

Multiple linear regression was calculated to investigate the relationship between geomorphic volume change, cattle access frequency, rainfall, and stream discharge. Results from the analysis are presented in Table 5 for Sites 1 and 2. This analysis was not performed for Site 3 due to insufficient data as no cattle presence was recorded for the duration of TLS campaigns 3 and 4 at this site (Table 3).

Four linear models with variations in predictors showed that geomorphic change was most strongly predicted by cattle access frequency at both Sites 1 and 2 (p = 0.002 and 0.003, respectively). Linear models with variations including cattle access and combinations of rainfall and stream discharge were insignificant additions to the models. This was despite some small increase of significance in the coefficients of determination when rainfall or stream discharge was included. Inclusion of all three predictors similarly indicated cattle access as the only significant variable at Sites 1 and 2 (p = 0.040 and 0.028, respectively), but the increase in the coefficient of determination was not significant at either site (Site 1 R^2 0.922 to 0.935, $p = 0.096$ and R^2 0.907 to 0.949, $p = 0.076$; Table 5).

Table 5

4. Discussion

This study used novel approaches to record instream cattle activity with motion activated digital cameras and monitor geomorphic stream bank change through campaigns of terrestrial laser scanning (TLS). Multiple linear regression models (Table 5) indicated that the geomorphic volume change observed at each study site could not be fully explained by rainfall and discharge processes alone. Indeed, the most parsimonious predictor of volume change at Sites 1 and 2 was the frequency of cattle access. Consistent with this relationship, the exclusion of cattle and resulting paucity of observations for Site 3, which prevented the same analysis, may account for the least amount of geomorphic volume loss being recorded at this site over the study period. Therefore, in spite of differences in cattle access frequency, the general pattern was consistent across all three sites that increasing stream bank volume loss occurred after periods of high-frequency instream cattle activity and resulted in direct modifications in stream bank morphology.

The monitored sites are representative of catchment areas whose stream bank slopes exceed published values for angles of friction characteristic for their soil matrix (e.g. US Forest Service 1994, p. 435). While this exceedance was rather small for Site 2 and Site 3, it was substantially larger for the bank slope angle at Site 1 (Table 2), which is indicative of a more cohesive bank material. Notably Site 1 also experienced the greatest volumetric loss. Therefore, bank slope as a likely factor contributing to erosion by cattle impact would require consideration for catchment scale studies which aim to compare bank erosion potential between different stream access sites. However, beyond bank dimensions such a comparative analysis would also have to include the investigation of numerous site specific soil properties and processes, whose complex interaction defines the incipient motion of cohesive bank material (Knight et al., 1998).

Other studies have also linked cattle access points to riparian zone deterioration and stream bank destabilisation (e.g. Hughes, 2016b; Peppler and Fitzpatrick, 2005). However, by using the results of the TLS campaigns (Table 4) in combination with particle size analysis, this study was able to indicate more specifically that approximately 27 - 41 % of stream bank lost through cattle access at the three sites was in the <2 mm particle size. This is an important fraction for river biological functioning and benthic ecological health. It impacts salmonid egg development by impeding hyporheic exchange and thus causes deoxygenation of gravel redds (Pattison et al., 2015; Sear et al., 2014). Downstream benthic impacts from access points could therefore be anticipated (Braccia and Voshell, 2007; Conroy et al., 2016).

While elevated downstream turbidity data did indicate periods when cattle accessed the study sites during low flow, increased turbidity in general was most prominent during high flow events, when the combined influences of local erosion and upstream sediment transfers could not be disentangled. O'Sullivan et al. (2019a) also found that cattle access levels of sediment deposition were spatially limited to the access point due to site characteristics and stream geometry. It is, therefore, difficult to predict the extent of the downstream influence of <2 mm particle size transfer from these three study sites in the Upper Bann. However, a useful first estimate based on fine sediment volume lost at Sites 1, 2 and 3, and assuming a uniform sedimentation depth (2 mm), the potential areal extent of stream bed impact is 196.7 m^2, 72.5 m^2 and 28.9 m^2, respectively, over the grazing season.

The spatial extent of this impact may be further compounded owing to the number of field parcels used for grazing cattle that bordered the stream network in the wider study area (147 in total in two sub-catchments – 64 % of the number of grazed field parcels and equivalent to 18.4 parcels km^{-2}), including field parcels with multiple access points. Considering the Upper Bann catchment as a whole and similar livestock dominated catchments, cattle access to streams and rivers may, therefore, act as substantial sources of (fine) sediment supply. Previous investigations undertaken within lowland agricultural catchments in the east of Ireland found that the number of cattle access points was 7-8 points km^{-1} of river (Jordan and Ryan, 2011; Jordan and Smietanka, 2013 cited in Conroy et al., 2016). This spatial extent could limit some fluvial sites to achieve acceptable ecological status owing to varying retention times and small catchment sizes (Kavanagh and Harrison, 2014; O'Sullivan et al., 2019a; Snell et al., 2014).

4.1 Management implications

A study by Zaimes and Schultz (2015) in the USA showed that removing cattle from riparian areas for ten years led to improvement in stream bank stabilisation. Similar investigations carried out by Laubel et al. (2003) in Denmark and Zaimes et al. (2008) in the USA showed that restricting cattle access to streams for periods from 6 months to three years reduced the potential of bank erosion considerably along with improving bank vegetation and recovery of previously impacted riparian areas. As regulations and time-limited incentives for excluding cattle from streams and rivers are established elsewhere (e.g. SI 605, 2017; Welsh Government, 2017; DAERA, 2019), the benefits of these services will be measured against expected water quality improvements. This study at least indicates that cattle exclusion can potentially reduce erosion of stream banks at cattle access points by 0.067 – 0.092 m^3 m^{-2} in a grazing period, 27 – 41 % of which is in the fine fraction.

This provides a first estimate of the reduction in sediment pressure expected from fencing measures in the Upper Bann and that can be used to scale up a volume of ‘saved’ sediment when all field parcel access points are enumerated and fenced. In exemplar catchments elsewhere with different soil characteristics and stocking densities, the method presented here can be applied more widely and is wholly transferable. It can be used as a tool for the reliable quantitative assessment of the reduction in sediment pressure resulting from national and international regulations and incentives to exclude cattle from direct access to streams.

5. Conclusions

Novel techniques of motion-capture and terrestrial laser scanning techniques (augmented with rainfall, stream discharge and water quality data) and results from multiple linear regression demonstrated that frequent cattle access to streams can result in significant loss of fine material from stream banks. This may contribute to localised instream sediment deposition and, while local in nature, the high number of access points identified in some catchments may result in a substantial loss in overall habitat quality.

Total and fine sediment (<2 mm) losses from the three stream bank areas in one grazing season were 0.092 m^3 m^{-2}, 0.067 m^3 m^{-2}, 0.071 m^3 m^{-2}, and 0.035 m^3 m^{-2}, 0.018 m^3 m^{-2}, 0.029 m^3 m^{-2}, respectively. This dataset and range give an indication of what sediment can be 'saved' from areas of stream bank with cattle exclusion in new or existing regulations or incentive schemes. The novel method presented here provides a transferable accounting framework for increasing the dataset in this and other catchment/soil types with similar livestock access issues.

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Figure and Table captions

Figure 1. Study catchment and location of cattle access points within two sub-catchments of the Upper Bann, Northern Ireland with ‘intensive’ (sub-catchment Bx: Site 1) and ‘less intensive’ (sub-catchment By - Sites 2 and 3) agricultural management. ‘Cattle present’ represents field parcels which have had cattle grazing at some point over twelve months prior to the study.

Figure 2. Time series plots showing periods of instream cattle access, turbidity, conductivity and stream discharge at Site 1 during a) low flow and b) a period of low flow flowed by a storm event. Turbidity (and conductivity to a lesser extent) show short duration increases with cattle access during low flow – but with a more pronounced increase in turbidity (and dilution of conductivity) during high flow in early November 2018.

Figure 3. Terrestrial Laser Scanning (TLS) point clouds showing the progressive geomorphic vertical change between first and last survey scans with areas in red depicting areas of high erosional change at Site 1 (a), 2 (b) and 3 (c). In the legends, colours with figures less than zero illustrate point differences where erosion is likely to have occurred.

Table 1. Summary information on physiography and land use/land cover for the Upper Bann catchment and two study sub-catchments.

Table 2. Morphological and hydraulic characteristics of study sites.

Table 3. Summary of instream cattle activity for study period 18th July to 11th December 2018 based on analysis of images recorded by the Victure HC200 motion-activated camera.

Table 4. Summary of bank geomorphic change recorded with the TLS, rainfall and stream discharge and surface runoff as they accumulated in survey intervals for the study period 18th July to 11th December 2018; surface runoff in mm as the quotient of stream discharge and sub-catchment area. For reference, the nearest long-term (1975 –2019) discharge monitoring station downstream of the study sites (101.7 km^2) has a ten day Q50 mean daily surface runoff of 10.8 mm and a Q10 surface runoff of 55.2mm (NRFA, 2020).

Table 5. Summary of multiple linear regression analysis undertaken for Sites one and two demonstrating the association between geomorphic surface change, cattle access frequency, rainfall and stream discharge accumulated in periods between TLS surveys.

Tables

Table 1. Summary information on physiography and land use/land cover for the Upper Bann catchment and two study sub-catchments.

Catchment	Area, km^2	Elevation, m	Land cover, %			Land use, %						Mean field area, ha	Mean drainage density, $km\ km^{-2}$
			Grass	Arable	Other	Beef	Dairy	Mixed livestock	Mixed livestock/arable	Sheep			
Upper Bann	220	50-630	95	3	2	26	13	32	11	18		0.94	1.04
Bx	3.8	54-300	60	30	10	12	29	35	18	6		1.83	1.36
By	4.2	60-630	90	5	5	37	21	32	0	10		0.93	2.03

Table 2. Morphological and hydraulic characteristics of study sites.

Site	Reach gradient (m km^{-1})	Stream width (m)	Bank height (m)	Bank length (m)	Bank slope (º)
1	11	2.30	1.5	7.5	60
2	13	2.05	4.0	2.0	45
3	15	4.15	1.2	2.0	40

Table 3. Summary of instream cattle activity for study period 18th July to 11th December 2018 based on analysis images taken with the Victure HC200 motion-activated camera.

Site	Survey period in 2018	No. of days between TLS	Cattle access frequency
1	18/07 → 02/08	15	38
	03/08 → 21/08	19	287
	22/08 → 13/09	23	169
	14/09 → 09/10	26	73
	10/10 → 20/11	43	578
	21/11 → 11/12	21	9
	Total	**150**	**1154**
2	18/07 → 02/08	15	34
	03/08 → 21/08	19	9
	22/08 → 13/09	23	112
	14/09 → 09/10	26	45
	10/10 → 20/11	43	89
	21/11 → 11/12	21	6
	Total	**150**	**295**
3	14/08 → 13/09	31	130
	14/09 → 09/10	26	0
	10/10 → 20/11	42	0
	21/11 → 11/12	21	0
	Total	**120**	**130**

Table 4. Summary of bank geomorphic change recorded with the TLS, rainfall, stream discharge and surface runoff as they accumulated in survey intervals for the study period 18th July to 11th December 2018; surface runoff in mm as the quotient of stream discharge and sub-catchment area. For reference, the nearest long-term (1975 –2019) discharge monitoring station downstream of the study sites (101.7 km^2) has a ten day Q50 mean daily surface runoff of 10.8 mm and a Q10 surface runoff of 55.2mm (NRFA, 2020).

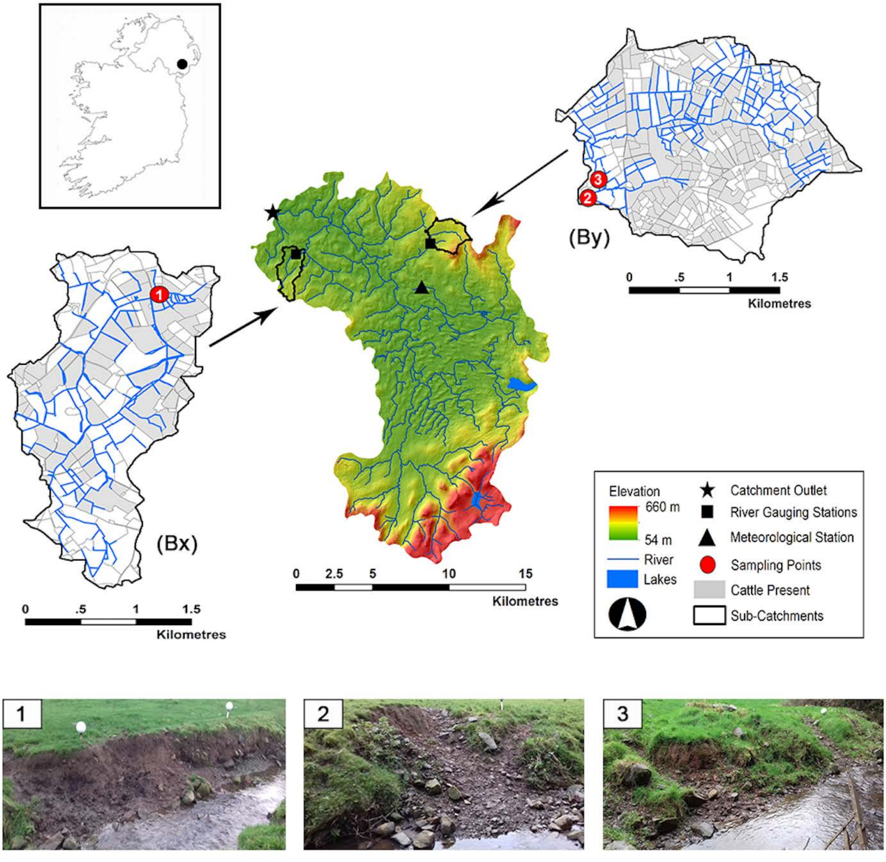
Site	Survey period in 2018	No. of days between TLS	Volumetric Change (m^3)	Rainfall (mm)	Stream Discharge (m^3)	Surface Runoff (mm)
1	18/07 - 02/08	15	0.068	102.6	342	0.2
	03/08 - 21/08	19	0.321	37.0	1,974	0.5
	22/08 - 13/09	23	0.142	35.0	1,642	0.8
	14/09 - 09/10	26	0.066	23.0	414	0.6
	10/10 - 20/11	43	0.402	133.0	86,078	20.9
	21/11 - 11/12	21	0.036	80.8	183,418	41.8
	Total	**150**	**1.035**	**411.4**	**273,868**	**69.0**
2	18/07 - 02/08	15	0.089	102.6	42,450	10.4
	02/08 - 21/08	19	0.052	37.0	16,093	3.9
	22/08 - 13/09	23	0.144	35.0	22,108	5.4
	14/09 - 09/10	26	0.095	23.0	18,635	4.6
	10/10 - 20/11	43	0.104	133.0	241,169	59.1
	21/11 - 11/12	21	0.053	80.8	262,929	64.4
	Total	**150**	**0.537**	**411.4**	**603,384**	**147.9**
3	14/08 - 13/09	31	0.11	58.6	28,322	6.9
	14/09 - 09/10	26	0.016	23.0	18,635	4.6
	10/10 - 20/11	42	0.008	124.4	241,169	59.1
	21/11 - 11/12	21	0.007	87.8	262,929	64.4
	Total	**120**	**0.141**	**293.8**	**551,055**	**135.1**

Table 5. Summary of multiple linear regression analysis undertaken for Sites one and two demonstrating the association between geomorphic volume loss, cattle access frequency, rainfall and stream discharge accumulated in periods between TLS surveys.

Study sites			**Coefficients**	**Standard error**	**t**	**Sig.**	**Multiple r^2**	**F-statistic**	**p-value**
Site 1	**Model 1**: Geomorphic Volume Loss ~ Cattle Access Frequency + Rainfall + Stream Discharge	Intercept	6.3×10^{-2}	5.0×10^{-2}	1.242	0.340	0.935	9.538	0.096
		Cattle	7.1×10^{-4}	1.5×10^{-4}	4.826	**0.040***			
		Rain	-3.5×10^{-4}	8.1×10^{-4}	-0.430	0.709			
		Discharge	-7.6×10^{-8}	4.3×10^{-7}	-0.177	0.876			
	Model 2: Geomorphic Volume Loss ~ Cattle Access Frequency + Rainfall	Intercept	6.3×10^{-2}	4.1×10^{-2}	1.518	0.226	0.934	21.115	0.017
		Cattle	7.2×10^{-4}	1.2×10^{-4}	6.129	**0.009****			
		Rain	-4.2×10^{-4}	5.7×10^{-4}	-0.740	0.513			
	Model 3: Geomorphic Volume Loss ~ Cattle Access Frequency + Stream Discharge	Intercept	4.9×10^{-2}	3.4×10^{-2}	1.464	0.239	0.929	19.52	0.019
		Cattle	6.8×10^{-4}	1.1×10^{-4}	6.221	**0.008****			
		Discharge	-1.7×10^{-7}	3.1×10^{-7}	-0.546	0.623			
	Model 4: Geomorphic Volume Loss ~ Cattle Access Frequency	Intercept	4.1×10^{-2}	2.7×10^{-2}	1.500	0.208	0.922	46.982	0.002
		Cattle	1.0×10^{-3}	1.0×10^{-4}	6.854	**0.002****			

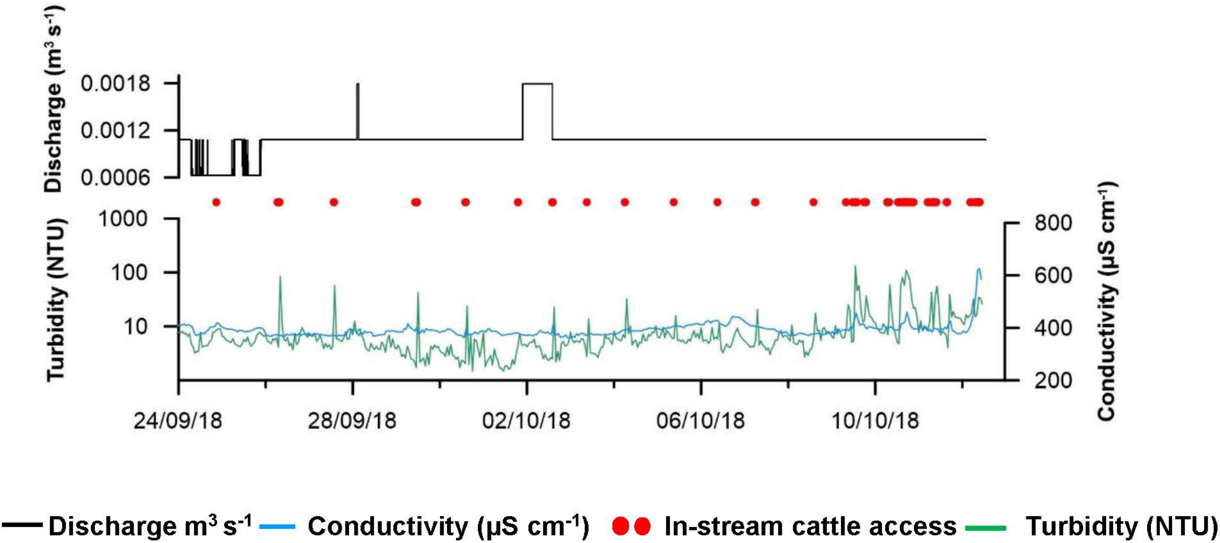
Site 2	**Model 1**: Geomorphic Volume Loss ~ Cattle Access Frequency + Rainfall + Stream Discharge	Intercept	5.7×10^{-2}	1.2×10^{-2}	4.598	0.044 *	0.949	12.321	0.076
		Cattle	7.5×10^{-4}	1.3×10^{-4}	5.817	**0.028** *			
		Rain	3.3×10^{-5}	1.9×10^{-4}	0.172	0.879			
		Discharge	-6.7×10^{-8}	6.4×10^{-8}	-1.047	0.405			
	Model 2: Geomorphic Volume Loss ~ Cattle Access Frequency + Rainfall	Intercept	5.9×10^{-2}	1.3×10^{-2}	4.690	0.018 *	0.921	17.380	0.022
		Cattle	1.0×10^{-3}	1.3×10^{-4}	5.858	**0.010****			
		Rain	1.0×10^{-4}	1.5×10^{-4}	-0.714	0.527			
	Model 3: Geomorphic Volume Loss ~ Cattle Access Frequency + Stream Discharge	Intercept	5.9×10^{-2}	0.8×10^{-2}	7.416	0.005**	0.948	27.314	0.012
		Cattle	1.0×10^{-3}	1.1×10^{-4}	7.107	**0.006****			
		Discharge	-5.9×10^{-8}	3.9×10^{-8}	-1.535	0.222			
	Model 4: Geomorphic Volume Loss ~ Cattle Access Frequency	Intercept	5.2×10^{-2}	0.8×10^{-2}	6.756	0.003**	0.907	39.021	0.003
		Cattle	1.0×10^{-3}	1.2×10^{-4}	6.247	0.003**			

Significance: *** p<0.001, ** p<0.01, * p<0.05



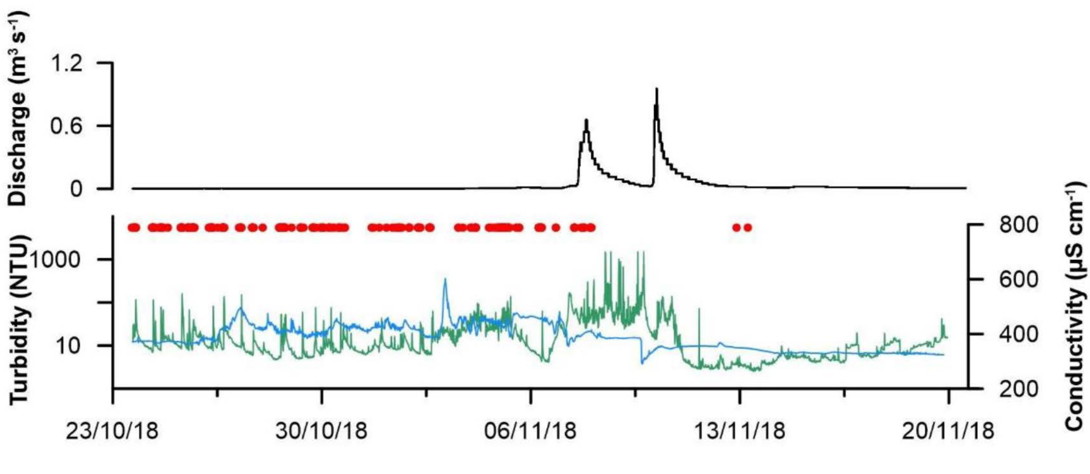
(By)
0 .5 1 1.5
Kilometres
(Bx)
0 .5 1 1.5
Kilometres
0 2.5 5 10 15
Kilometres
Elevation
660 m
54 m
River
Lakes
Catchment Outlet
River Gauging Stations
Meteorological Station
Sampling Points
Cattle Present
Sub-Catchments
1
2
3

a)

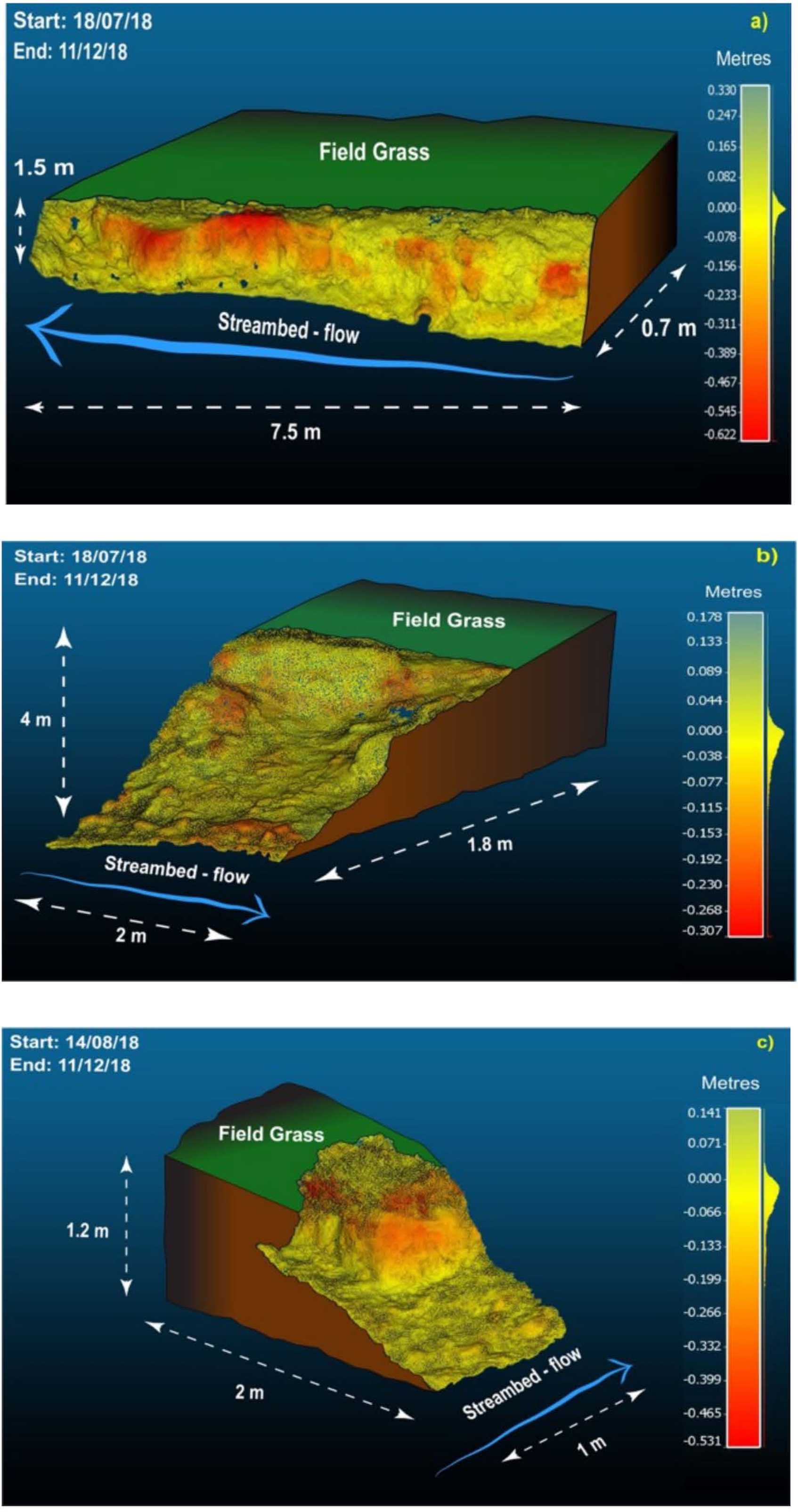


Discharge (m3 s-1)
0.0018
0.0012
0.0006
1000
100
10
Turbidity (NTU)
800
600
400
200
Conductivity (µS cm-1)
24/09/18
28/09/18
02/10/18
06/10/18
10/10/18
Discharge m3 s-1
Conductivity (µS cm-1)
In-stream cattle access
Turbidity (NTU)

b)



Discharge (m3 s-1)
1.2
0.6
0
Turbidity (NTU)
1000
10
800
600
400
200
Conductivity (µS cm-1)
23/10/18
30/10/18
06/11/18
13/11/18
20/11/18



Start: 18/07/18
End: 11/12/18
a)
Metres
0.330
0.247
0.165
0.082
0.000
-0.078
-0.156
-0.233
-0.311
-0.389
-0.467
-0.545
-0.622
Field Grass
1.5 m
Streambed - flow
0.7 m
7.5 m
Start: 18/07/18
End: 11/12/18
b)
Metres
0.178
0.133
0.089
0.044
0.000
-0.038
-0.077
-0.115
-0.153
-0.192
-0.230
-0.268
-0.307
Field Grass
4 m
1.8 m
Streambed - flow
2 m
Start: 14/08/18
End: 11/12/18
c)
Metres
0.141
0.071
0.000
-0.066
-0.133
-0.199
-0.266
-0.332
-0.399
-0.465
-0.531
Field Grass
1.2 m
2 m
Streambed - flow
1 m

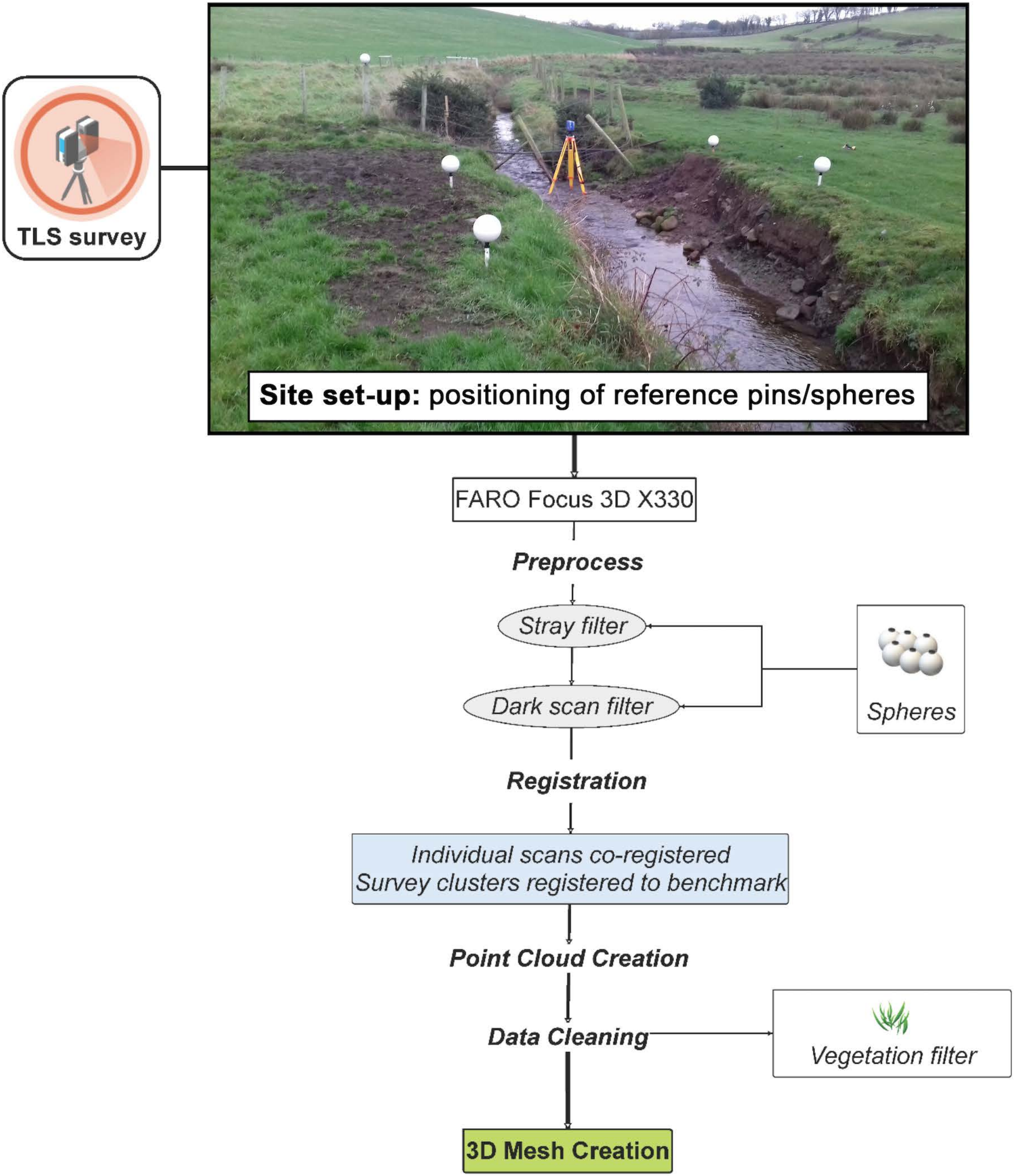
Table S1. Accuracy of TLS surveys throughout the investigation as determined by the mean target distance errors. Each survey cluster had a mean target distance error of less than 5.32 mm. To calculate geomorphic volume loss, each survey cluster required registration to a benchmark survey, i.e. the first survey undertaken for each site.

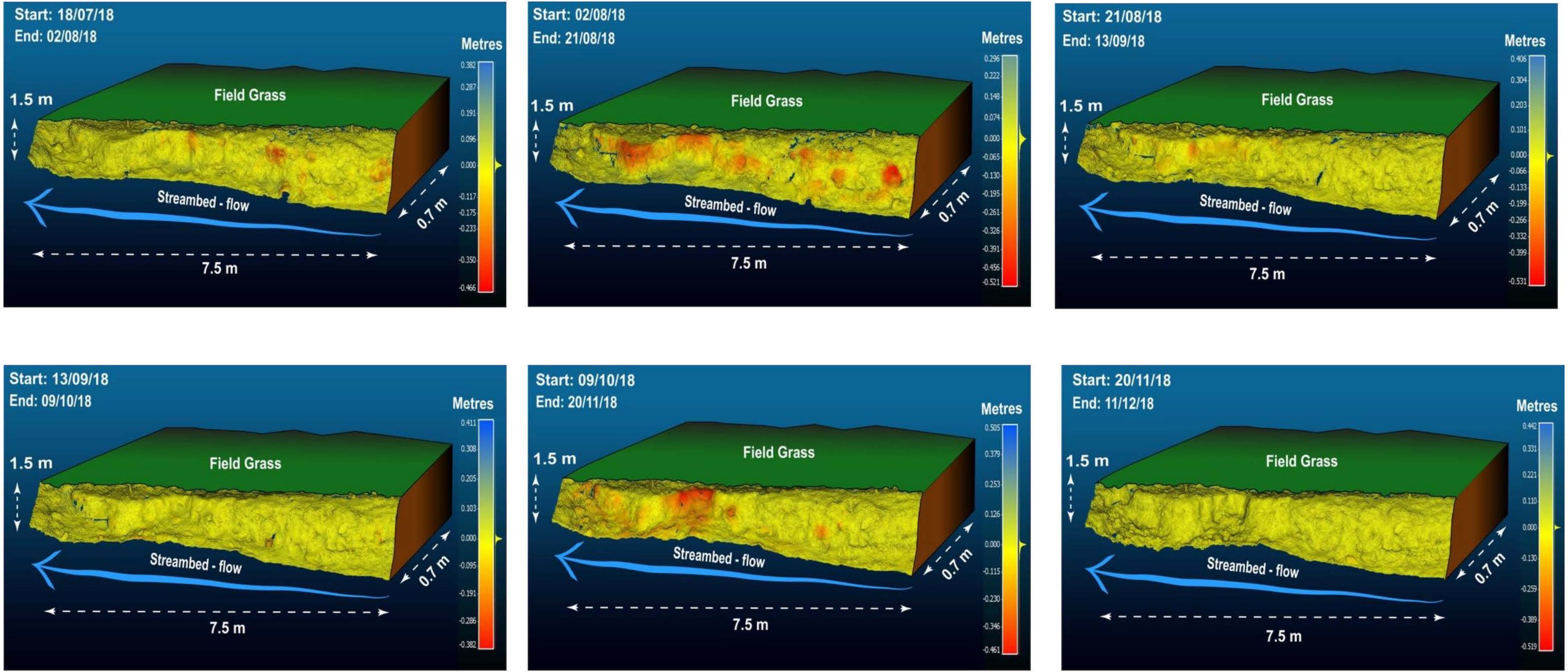
	Mean target distance error (mm)		
Survey dates	Site 1	Site 2	Site 3
02/08/2018	2.68	3.59	
21/08/2018	3.08	5.09	1.93
13/09/2018	4.99	5.32	2.18
09/10/2018	5.01	3.56	2.43
20/11/2018	4.74	4.65	2.97
11/12/2018	4.96	4.17	3.77

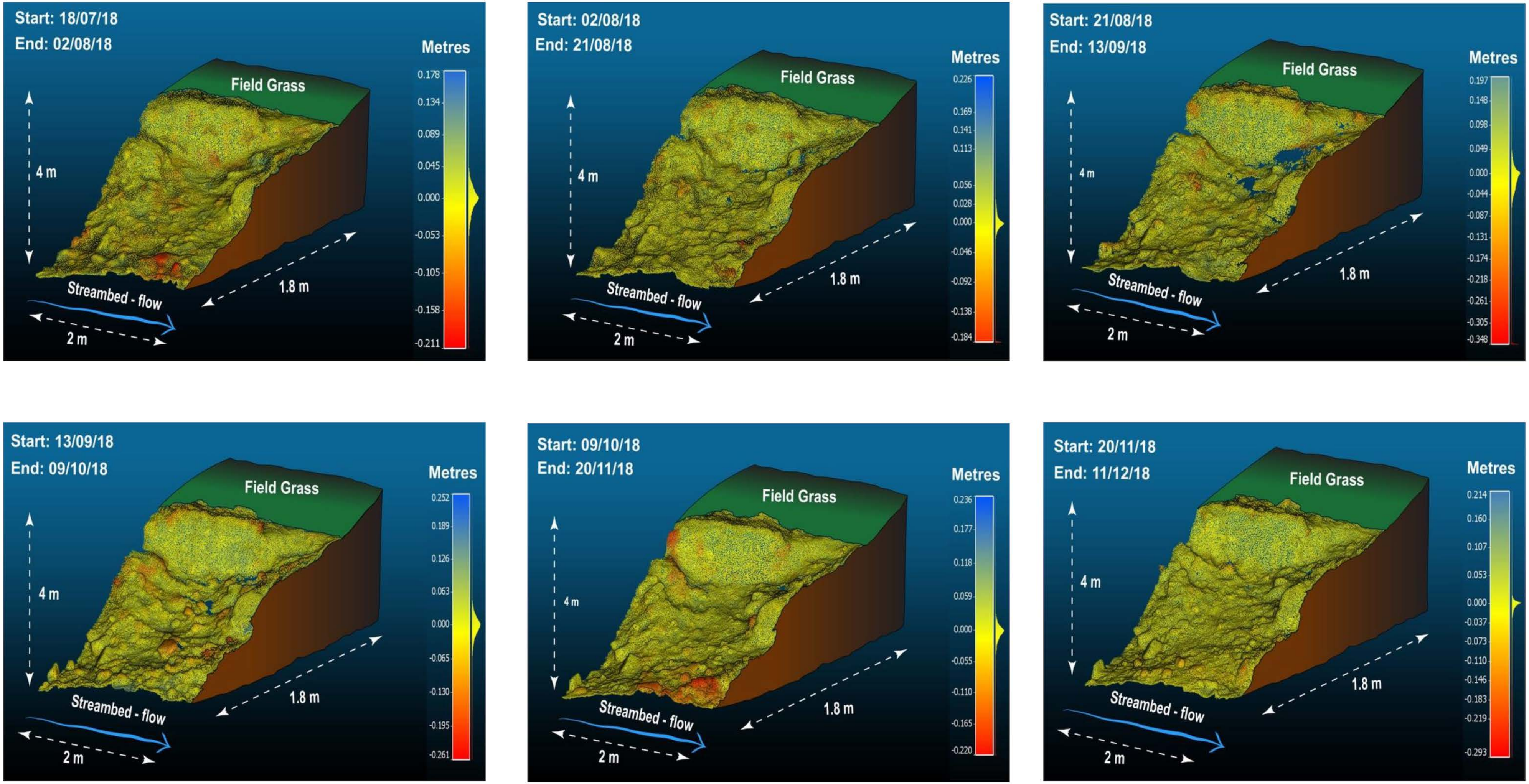
Table S2. Soil texture analysis (particle size <2mm)

Site	**% Sand**	**% Silt**	**% Clay**
1	47.2	29.8	23.0
2	50.1	36.9	13.0
3	67.2	23.4	9.4

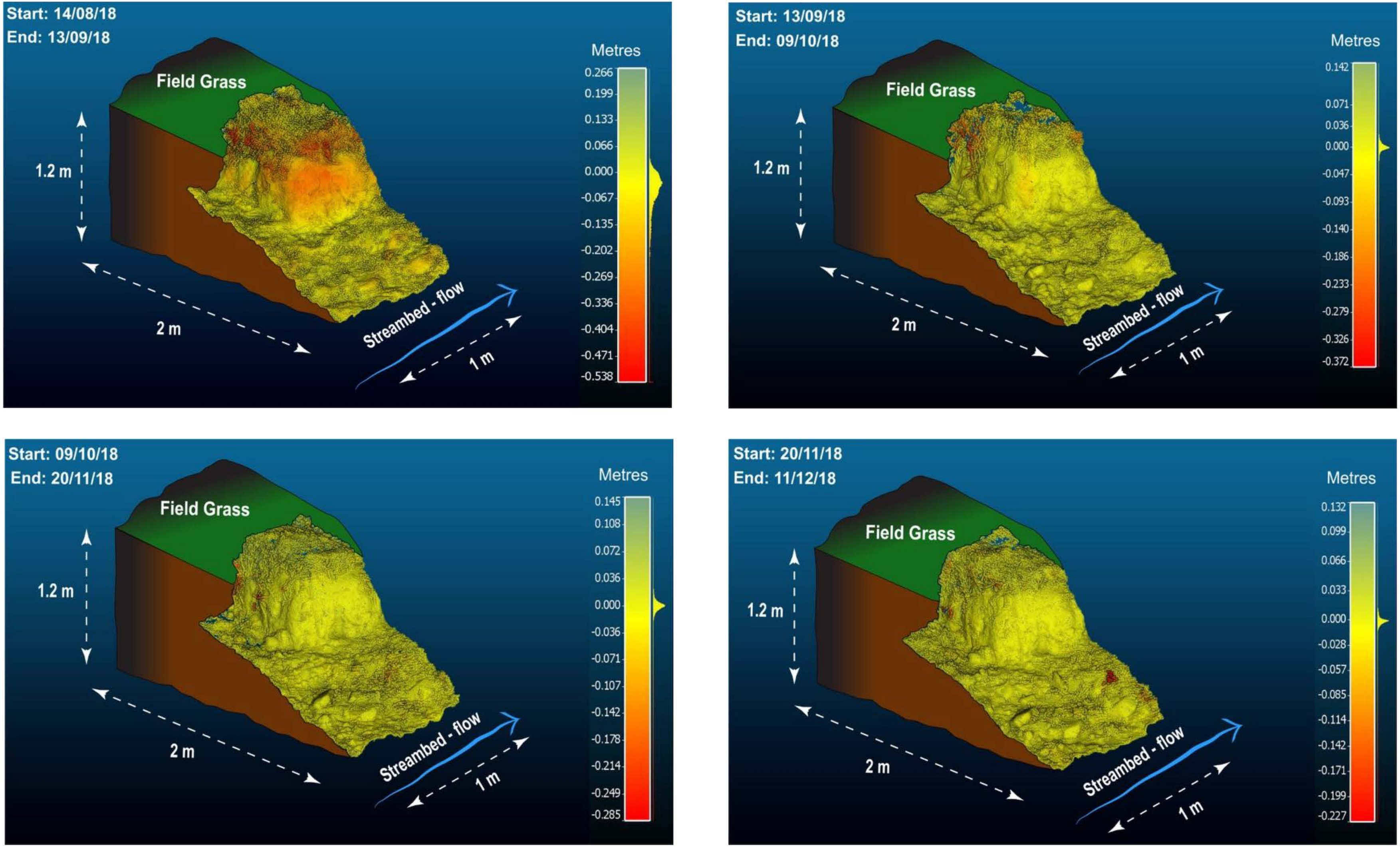

1
2
3


TLS survey
Site set-up: positioning of reference pins/spheres
FARO Focus 3D X330
Preprocess
Stray filter
Dark scan filter
Spheres
Registration
Individual scans co-registered
Survey clusters registered to benchmark
Point Cloud Creation
Data Cleaning
Vegetation filter
3D Mesh Creation


Start: 18/07/18
End: 02/08/18
Metres
0.382
0.287
0.191
0.096
0.000
-0.117
-0.175
-0.233
-0.350
-0.466
Field Grass
1.5 m
Streambed - flow
0.7 m
7.5 m
Start: 02/08/18
End: 21/08/18
Metres
0.296
0.222
0.148
0.074
0.000
-0.065
-0.130
-0.195
-0.261
-0.326
-0.391
-0.456
-0.521
Field Grass
1.5 m
Streambed - flow
0.7 m
7.5 m
Start: 21/08/18
End: 13/09/18
Metres
0.406
0.304
0.203
0.101
0.000
-0.066
-0.133
-0.199
-0.266
-0.332
-0.399
-0.531
Field Grass
1.5 m
Streambed - flow
0.7 m
7.5 m
Start: 13/09/18
End: 09/10/18
Metres
0.411
0.308
0.205
0.103
0.000
-0.095
-0.191
-0.286
-0.382
Field Grass
1.5 m
Streambed - flow
0.7 m
7.5 m
Start: 09/10/18
End: 20/11/18
Metres
0.505
0.379
0.253
0.126
0.000
-0.115
-0.230
-0.346
-0.461
Field Grass
1.5 m
Streambed - flow
0.7 m
7.5 m
Start: 20/11/18
End: 11/12/18
Metres
0.442
0.331
0.221
0.110
0.000
-0.130
-0.259
-0.389
-0.519
Field Grass
1.5 m
Streambed - flow
0.7 m
7.5 m



Start: 18/07/18
End: 02/08/18
Metres
0.178
0.134
0.089
0.045
0.000
-0.053
-0.105
-0.158
-0.211
Field Grass
4 m
1.8 m
Streambed - flow
2 m
Start: 02/08/18
End: 21/08/18
Metres
0.226
0.169
0.141
0.113
0.056
0.028
0.000
-0.046
-0.092
-0.138
-0.184
Field Grass
4 m
1.8 m
Streambed - flow
2 m
Start: 21/08/18
End: 13/09/18
Metres
0.197
0.148
0.098
0.049
0.000
-0.044
-0.087
-0.131
-0.174
-0.218
-0.261
-0.305
-0.348
Field Grass
4 m
1.8 m
Streambed - flow
2 m
Start: 13/09/18
End: 09/10/18
Metres
0.252
0.189
0.126
0.063
0.000
-0.065
-0.130
-0.195
-0.261
Field Grass
4 m
1.8 m
Streambed - flow
2 m
Start: 09/10/18
End: 20/11/18
Metres
0.236
0.177
0.118
0.059
0.000
-0.055
-0.110
-0.165
-0.220
Field Grass
4 m
1.8 m
Streambed - flow
2 m
Start: 20/11/18
End: 11/12/18
Metres
0.214
0.160
0.107
0.053
0.000
-0.037
-0.073
-0.110
-0.146
-0.183
-0.219
-0.293
Field Grass
4 m
1.8 m
Streambed - flow
2 m


Start: 14/08/18
End: 13/09/18
Field Grass
1.2 m
2 m
Streambed - flow
1 m
Metres
0.266
0.199
0.133
0.066
0.000
-0.067
-0.135
-0.202
-0.269
-0.336
-0.404
-0.471
-0.538
Start: 13/09/18
End: 09/10/18
Field Grass
1.2 m
2 m
Streambed - flow
1 m
Metres
0.142
0.071
0.036
0.000
-0.047
-0.093
-0.140
-0.186
-0.233
-0.279
-0.326
-0.372
Start: 09/10/18
End: 20/11/18
Field Grass
1.2 m
2 m
Streambed - flow
1 m
Metres
0.145
0.108
0.072
0.036
0.000
-0.036
-0.071
-0.107
-0.142
-0.178
-0.214
-0.249
-0.285
Start: 20/11/18
End: 11/12/18
Field Grass
1.2 m
2 m
Streambed - flow
1 m
Metres
0.132
0.099
0.066
0.033
0.000
-0.028
-0.057
-0.085
-0.114
-0.142
-0.171
-0.199
-0.227